CSP, BGA, and SM Packages for Harsh Environmental Applications

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Abstract

Different aspects of advanced surface mount package technology have been investigated for aerospace applications. Three key areas included the assembly reliability of conventional Surface Mount (SM), Ball Grid Arrays (BGAs), and Chip Scale Packages (CSPs).

More than 200 SM packages were assembled using LCCs, J-leads, and gull wings components on FR-4 Printed Wiring Boards (PWBs). These were subjected to thermal cycle testing and solder joint damage propagation over time was recorded using visual and scanning electron microscopy. Two-Weibull parameter distributions were used to present cycles to failures results.

Reliability of BGAs was assessed as part of a consortium effort led by the Jet Propulsion Laboratory. Nearly 200 test vehicles, each with four packages, were assembled and tested using an experiment design. The most critical variables incorporated in the experiment were package type, board material, surface finish, solder volume, and environmental condition. The BGA test vehicles were subjected to thermal and dynamic environments representative of aerospace applications. The test vehicles were monitored continuously to detect electrical failure and their failure mechanisms were characterized.

In the CSP program, a MicrotypeBGA consortium with industry-wide support was organized to address technical regarding the interplay of CSP package type, 1/0 counts, PWB materials, and the manufacturing variables on quality and reliability of board level assembly.

'l'his paper will compare only the most current thermal cycling test results under different cycling ranges for 20-,28-, and 68-pin LCCs, 68-pin gull wing cerquads, ceramic BGA with 625 1/0, and plastic BGA packages with313 and 352 1/0s. The board level reliability of CSP assembly will also be reviewed, projected, and compared to the SM package assembly test results.

INTRODUCTION

In surface mount technology (SMT), electronic packages arc mounted and terminated directly onto the PWB surface rather than inserting the leads into plated through-holes (PTHs). Survey results from the Issues in Global Technology survey (Surface Mount Technology Magazine, October 1996 issue) indicate that the percentage of surface-mount chips is expected to increase in 1997 from 47.5 to 49.6, whereas through-hole technology use is expected to decline from 26.9 to 23.3.

There are several surface mount package styles, both active and passive. Active devices are divided into those with terminations of leads on the periphery of the component, two sides or four sides, or those with terminations (either pads or solder bumps) over much of the bottom of the component,

In the SMT program, peripheral leaded and leadless board assemblies were evaluated in a concurrent engineering. Different aspects of SM technology evaluation included design, modeling, manufacturing, test, deployment (aging) cycle, and quality assurance methodology development. A summary of the most recent reliability test results are presented,

BGA is an important technology for utilizing higher pin counts, without the attendant handling and processing problems of the peripheral leaded packages. They are also robust in processing because of their higher pitch (0,050 inch typical), better lead rigidity, and self-alignment characteristics during reflow processing.

BGAs' solder joints cannot be inspected and reworked using conventional methods and arc not well characterized for multiple double sided assembly processing methods. In high reliability SMT assembly applications, e.g. space and defense, the ability to inspect the solder joints visually has been standard and has been a key factor for providing confidence in solder joint reliability.

'I'o address many common quality and reliability issues of BGAs, JPL organized a consortium with sixteen members in early 1995. Diverse membership including military, commercial, academia, and infrastructure sectors which permitted a concurrent engineering approach for resolving many challenging technical issues.

Emerging Chip Scale Packages (CSPs) are competing with bare die assemblies and are now at the stage Ball Grid Arrays (BGAs) were about two years ago. These packages provide the benefits of small size and performance of the bare die or flip chip, with the advantage of standard die packages. Availability of board level solder joint reliability information is critical to the acceptance of CSPS as alternative packages. This paper will present test data and projection for BGA and CSP assembly reliability.

SURFACE MOUNT TECHNOLOGY PROGRAM

Test Vehicle Assembly and Thermal Cycling

The SMT program involved the usc of a single ceramic component, **0.050** inch pitch, soldered to an epoxy-fiberglass FR-4 board[1]. LCCs, J-lead cerquads, and gull wing cerquads were the SMT components.

Test vehicles were subjected to a cycle profile with long duration to assure near complete creeping. This long duration cycle started at 25°C with a decrease rate of 2°C per minute to -55°C with an oven dwell setting of 45 minutes. The temperature increase to 100"C was at a rate of change of 2°C per minute with an oven dwell setting of 45 minutes, followed by a decrease of temperature to 25°C completes the cycling. The duration of each cycle is 246 minutes.

Thermomechanical cycle testing assemblies having LCCs and Gull Wings are now complete and all of assemblies have failed (open circuit). Failures were detected by Anatech® and verified by visual inspection. The testing of the J-leads is still being continued and now (July 1997) has reached about 4,500 cycles with no signs of failure.

Test Results

Figure 1 shows cycles to failure for 68-, 28-, and 20-pin LCC assemblies. The cycles to failure were ranked from low to high and failure distribution percentiles were approximated using median plotting position, $F_i = (i-0.3)/(n+0.4)$. As expected, there was a large spread in cycles to failure because of the common variance that are associated with materials and manufacturing conditions including solder joint volume, quality of joint, and location. The first failure for the 68-pin LCCS was detected at 53 cycles while the last sample failed after 139 with 93 average cycles. 28-pin LCCS failed at much higher cycles in the range of 352 to 908 with 660 average cycles. The 20-pin cycles to failure were in the same range as for those of 28-pins and failed within 573 to 863 averaging 674 cycles.

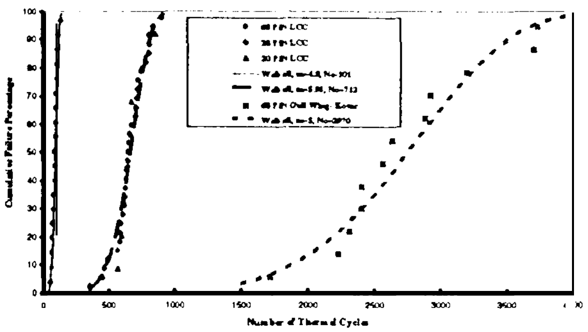

Figure 1. Cumulative Failure Distribution Plots for LCC and Gull Wing Assemblies

If only Distance to Neutral Points (DNPs) are considered, the 20-pin LCCS with shorter DNP than the 28-pin, should have failed at higher cycles since cycles to failure is directly proportional to DNP. However, cycles to failure also inversely depends on the effective solder fillet height, Solder fillet height for 20- and 28-pin LCCs was 0.021 and 0.033 inches respectively, which is lower for a 20-pin resulting in higher shear strain for the same CTE mismatch displacement. The difference in part sizes could have been off-set by the difference in the fillet heights.

All 68-pin gull wing assemblies failed at much higher cycles. Assemblies with Kovar alloy leads were failed between 1,720 cycles and about 3,750 cycles. Cycles to failure are shown in Figure 1. Gull wings with Alloy 42 lead failed at higher cycles and results are not presented here.

Weibull Distribution

Often, two-parameter Weibull distributions have been used to characterize failure distribution and provide modeling for prediction in the areas of interest. The Weibull cumulative failure distribution was used to fit

68- and 28- pin LCCs' cycles to failure data. The equation is

$$F(N) = 1 - \exp\left(-(N/No)^m\right)$$

where

F(N) is the cumulative failure distribution function
N is the number of thermal cycles
No is a scale parameter that commonly is referred to as characteristic life, and is the number of thermal cycles with 63.2% failure occurrence
m is the shape parameter and is inversely proportional to the coefficient of variation
(CV) by 1.2/CV, as **m** increases, spread in cycles to failure decreases

This equation, in double logarithm format, results in a straight line. The slope of the line will define the Weibull shape parameter. The cycle to failure data in log-log were fitted in a straight line and the two Weibull parameters were calculated.

The Weibull graphs are plotted in Figure 1 for SM packages. For 68-pin LCCs, the scale and shape parameters were 101 cycles and 4.8, respectively. These were 712 cycles and 5.95 for the 28-pin LCCs. Both data sets showed excellent linear correlation in log-log plots with a coefficient of correlation of at least 0.97.

Weibull scale and shape parameter for gull wings with Kovar leaded packages were 5 and 2970, respectively. The coefficient of linear correlation in log-log plot was 0.94. One reason of lower coefficient value could be due to manual checking for failure up to 50 cycle intervats above 2,600 cycles.

BALL GRID ARRAY PROGRAM

Test Vehicle Configuration

The two test vehicle assemblies included plastic and ceramic packages[2,3]. Both FR-4 and polyimide PWBS with six layers, 0.062 inch thick, were used.

Plastic packages covered the range from OMPAC to SuperBGAs (SBGAs). These were:

- Two peripheral SBGAs, 352 and 560 1/0
- Peripheral OMPAC 352 1/0, PBGA 352 and 256 1/0
- Depopulated full array PBGA 313 I/Os
- 256 QFP, 0.4 mm Pitch

In SBGA, the IC die is directly attached to an oversize copper plate providing better heat dissipation efficiency than standard PBGAs. The solder balls for plastic packages were eutectic (63 Sn/37Pb).

Ceramic packages with 625 1/0s and 361 1/0s were also included in our evaluation. Ceramic solder balls (90Pb/10Sn) with 0.035 inch diameters had a high melting temperature. These balls were attached to the ceramic substrate with eutectic solder (63 Sn/37Pb). At reflow, package side eutectic solder and the PWB side eutectic paste will be reflowed to provide the electro-mechanical interconnects.

Plastic packages had dummy and daisy chains with the daisy chains on the PWB designed so as to be able to monitor critical solder joint regions. Most packages had four daisy chain patterns, 560 1/0 had five, and the QFP had one.

Two test vehicles were assembled:

- Type 1, ceramic and plastic BGA packages with nearly 300 1/0s
- Type 2, ceramic and plastic BGA packages with nearly 600 1/0s. Also utilized were a 256 leaded and a 256 plastic BGA package for evaluating and directly comparing manufacturing robustness and reliability.
- Assemblies with water soluble flux were cleaned in an Electrovert H500. Those with RMAs were cleaned used Isopropyl Alcohol (I PA) and a 5% saponifier.
- All fine pitch QFPs had to be reworked for bridges.

Thermal Cycling

Two significantly different thermal cycle profiles were used at two facilities. The cycle A condition ranged -30 to 100"C and had increase/decrease heating rate of 2°C and dwell of about 20 minutes at the high temperature to assure near complete creeping. The duration of each cycle was 82 minutes.

The cycle B condition ranged -55 to 125°C. It could be also considered a thermal shock since it used a three regions chamber: hot, ambient, and cold. Heating and cooling rates were nonlinear and varied between 10 to 15 °C/min. with dwells at extreme temperatures of about 20 minutes. The total cycle lasted approximately 68 minutes. BGA test vehicles were continuously monitored through a LabView system at both facilities.

Similarly to SM assemblies, the criteria for an open solder joint specified in IPC-SM-785, Sect. 6.0, were used as guidelines to interpret electrical interruptions. Failures for ceramic packages usually could be verified by visual inspection of perimeter solder joints, but this was not the case for plastic packages. Generally once the first interruption was observed, there were many additional interruptions within 10% of the cycle life. In several instances, a few non-consecutive early interruptions were not followed by additional interruptions till significantly later stages of cycling. This was found more with plastic packages.

BGA Thermal Cycling Results

10 link our data with those of conventional SMT test results, a few TVs were subjected to a long duration cycle specified earlier in the SM section (-55°C to 100"C).

Figure 2 compares cycles to failure for CBGA 625 1/0s and the 68-, 28-, and 20-pin ceramic Leadless (LCC) assemblies. Similarly to SM assemblies, the cumulative failure percentiles were approximated using a median plotting position, $F_i = (i-0.3)/(n+0.4)$.

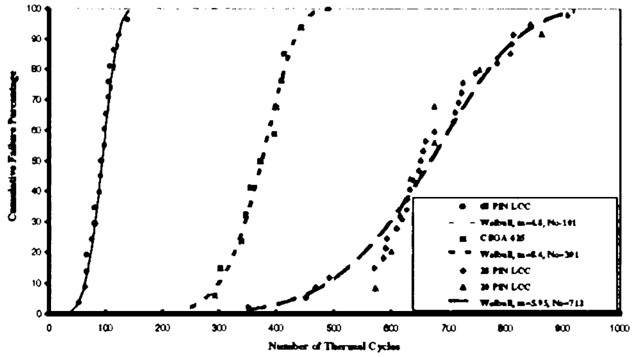

Figure 2 **Cumulative Failure Distribution Plots for CBGA 625 I/O and LCC Assemblies Subjected to -55°C<->100°C with 246 minute duration**

For this set of BGA assemblies, failures for electrical opens were detected manually. These sets of BGA test vehicles were removed periodically and daisy chain resistances measured for opens. Other BGA test vehicles were continuously monitored through a LabView system designed for this purpose[4].

The first failure for CBGA was detected at 312 cycles and occurred between 292 and 312 cycles. The last failure checked at 450 cycles occurred between 439 and 450 cycles. The Weibull cumulative failure distribution was used to fit cycles to failure data. The Weibull scale and shape parameters for CBGA were 391 cycles and 8.4 respectively

Figure 3 includes cycles to failure test results for CBGA 625 1/0s assemblies subjected to cycle A conditions. Results include assemblies on polyimide and FR-4 with different surface finishes as well as different solder volumes. The thermal cycling oven temperature settings and temperature profile is also shown. Daisy chains of test vehicles were continuously monitored for failure detection. 'l'he 2P Weibull scale and shape parameters were 424 and 9.1. Five highest points, four representing those with Ni/Au and one with high solder volume, were excluded in order to get a better fit to data,

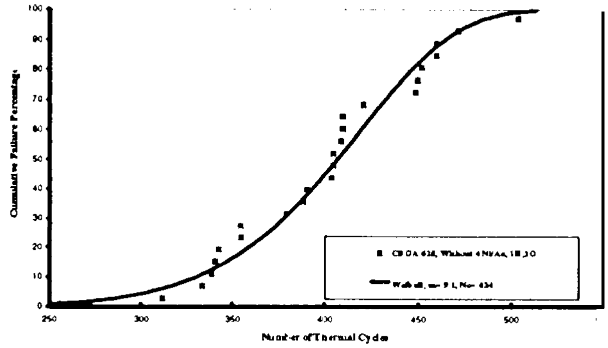

Figure 3 Cumulative Failure Distribution Plots for CBGA 625 I/O and LCC Assemblies Subjected to -3O"C.C->1OO"C with 82 minute duration

PBGA 313 and SBGA 352/A & B Cycles

Figure 4 shows cycles (o first failure for PBGA 313 and SBGA 352 subjected to B cycling for assemblies on polyimide and FR-4 PWBs[4].. The most current PBGA 313 assemblies that failed under cycle A conditions are afso included in the plots for comparison. These assemblies include those reflowed with low, standard, and high solder paste levels. Similarly to SM assemblies, the cycles to failure were ranked from low to high and failure distribution percentiles were approximated using median plotting position, $F_i = (i-0.3)/(n+0.4)$. Weibull parameters will be generated when all failure data are gathered.

CSP BOARD LEVEL RELIABILITY

Introduction

CSPS arc defined as packages that arc up to 1.2 or 1.5 times larger than the perimeter or the area of the die, respectively. Many manufacturers now refer to CSPS as packages that are the miniaturized version of their previous generation. This packaging accomplishes many purposes, including the following:

- Provides solder balls and leads that are compatible with the PWB pads for reflow assembly processes, whereas aluminum pads do not,
- Redistributes the tight pitch of the die to the pitch level that is within the norm of PWB fabrication. The small sizes of CSPs do not permit significant redistribution and the current cost-effective PWB

fabrication limits full adoption of the technology, especially for high 1/0 counts.

- Protects the dic from physical and alpha radiation damages, and provides a vehicle for thermal dissipation and case of die functionality testing.

CSPS generally have been categorized based on their fundamental structures. These are:

- Interposer packages with either flex or rigid substrate
- Wafer level molding and assembly redistribution
- Lead On Chip (LOC) packages.

Currently, most of this data are those that were generated for package qualifications by manufacturers with very limited published information available on assembly reliability. These data are of limited value to the end user since often (hey have been collected under significantly different manufacturing and environmental conditions or for packages with different pin counts.

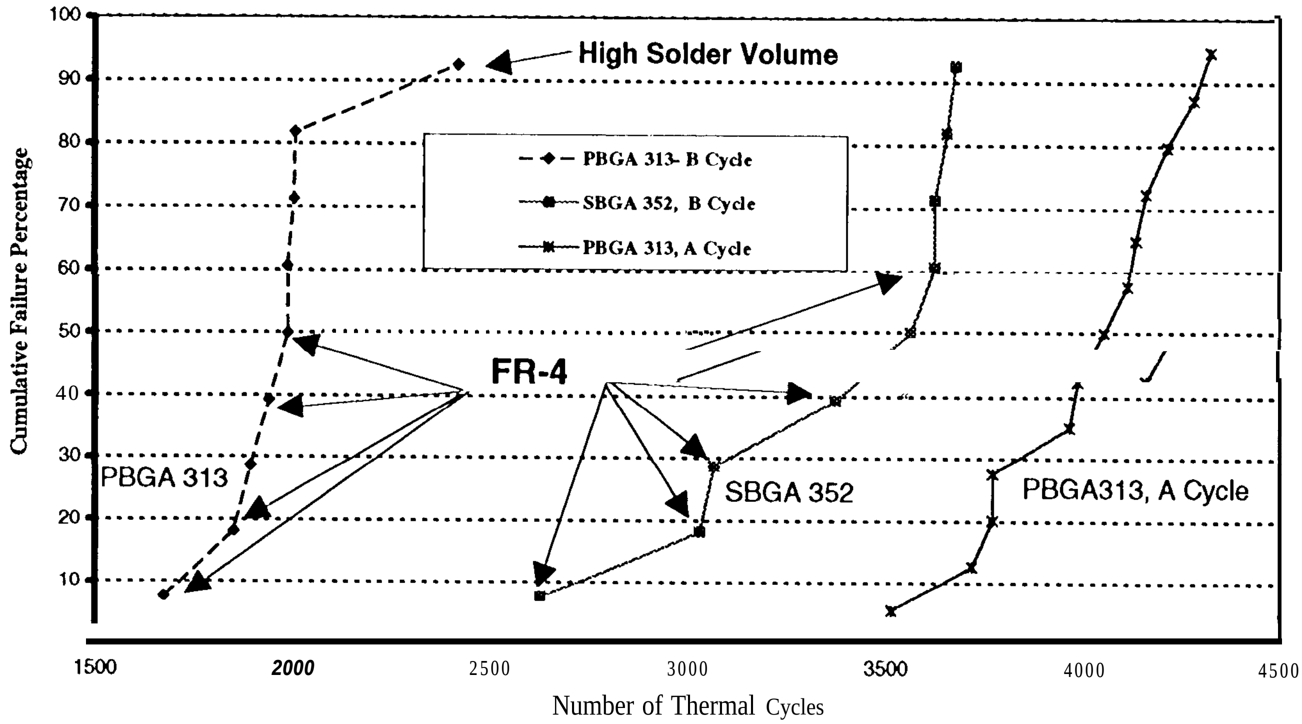

Figure 4 Cycles to Failure for PBGA 313 & SBGA 352 Assemblies (-55°C to 125°C, A) & (-30°C to 100°C)

Currently, most of this data are those that were generated for package qualifications by manufacturers with very limited published information available on assembly reliability. These data are of limited value to the end user since often they have been collected under significantly different manufacturing and environmental conditions or for packages with different pin counts.

Reliability y results of those gathered from literature and projection based on a modified Coffin-Manson relationship were compared to SMT test data[5].

Consortium to Assess CSPs' Board Level Reliability

For wider applications of this CSP technology, the potential user will need design reliability data for its design since often they have no resources, time, or ability to perform complex environmental characterizations. JPL has formed a consortium with the objectives of addressing many technical issues regarding the interplay of package type, 1/0 counts, PWB materials, surface finish, and manufacturing variables for the quality and reliability of assembly packages

Currently, the JPL-led MicrotypeBGA consortium has defined packages for the test vehicles and is in the process of designing of the test vehicles. It is anticipated that more than 300 test vehicles will be assembled and subjected to various environmental conditions representative of space and military as well as commercial applications.

CONCLUSIONS

SMA Reliability

- Among the surface mount assemblies, LCCs with 68 terminations showed lowest and 68-pin J-lead showed the highest thermal cycles to failure. Leaded assemblies lasted an order of magnitude higher than leadless.

- The 20- and 28-pin LCC assemblies failed at very similar cycles possibly differences in thermal strain due to part size could have been off-setted by the solder fillet heights. Cycles to failure is directly proportional to DNP and inversely depends on the effective solder fillet height. Solder fillet height for 20- and 28-pin 1.CCS was .021 and .033 inches respectively.

BGA Packages and Assembly Reliability

- Ceramic packages failed much earlier than their plastic counterparts because of their much larger CTE mismatch on FR-4/Polyimide boards. Cycles to electrical failure depend on many parameters including cycling temperature range and package size (1/0).

- Ceramic packages with 625 1/0s were first to show signs of failure among the ceramic (CBGA 361) and plastic packages (SBGA 560, SBGA 352, OMPAC 352, and PBGA 256) when cycled to different temperature ranges.

- Cycles to failures for a long duration cycle (-55°C to 100°C) and a modified version used for BGA (-30°C to 100°C) did not follow a Coffin-Manson relationship. The data set showed an almost linear reduction with delta temperature (Al') rather than a near square power reduction projected by the model,

- Cycles to failure results for two temperature profiles (long duration cycle and A cycle conditions) are in agreement with the school of thought that suggest low temperature exposure is less critical than high temperature, and time beyond the creep threshold at high temperature has no significant effect on eutectic solder joint failure.

- Joint failure mechanisms for assemblies exposed to two cycling ranges at two facilities were different. Ceramic 'assemblies cycled in the range of -30°C to 100"C showed cracking initially at both interconnections with final separation generally from the board side through the eutectic solder. The board side joint showed signs of pin hole formation prior to cracking and complete joint failure. This failure mechanism is similar to those reported in literature for O°C to 100"C thermal c ycles.

- The PBGAs with 313 1/0, depopulated full arrays, were first among the PBGAs to fail with both cycling ranges. It has been well established that this configuration, with solder balls under the die, is not optimum from a reliability point of view.

- Solder volume is generally considered to have negligible effect on plastic package assembly reliability. One PBGA 313 package that was assembled with a high solder paste volume under cycle B exposure showed the highest number of cycles to failure. This will be assessed when data for cycle A bccomc available.

- The 352 SBGA with no solder balls under the die showed much higher cycles to failure than the PBGA 313 when subjected to cycle B conditions.

- For cycle B conditions, plastic package assemblies (PBGA 313 and SBGA 352 on polyimide) generally failed at a higher number of cycles than those on FR-4.

CSP Assembly Reliability

- The board level reliabilities of most CSP packages are comparable or better than their LCC with similar I/O counts. These packages, however, are not as robust as leaded packages including gull wing and J-leads.
- Board level solder joint reliability information is critical to the acceptance of CSPs as alternative packages. It is the objectives of the JPL-led MicrotypeBGA consortium to help in developing this aspect of technology infrastructure.

REFERENCES

1. R. Ghaffarian. "SMT Solder Joint Reliability y/Workmanship Environmental Test Results Correlat ion for LCC Assemblies," 20th Annual Electronics Manufacturing Seminar Proceedings, February 19%
2. R. Ghaffarian, "Area Array Technology Evaluation for Space and Military Applications", The 1996 International Flip Chip, Ball Grid Array, TAR and Advanced Packaging Symposium Proceedings, Feb. 13-16, 19%.
3. R. Ghaffarian, "CBGA/PBGA Package Planarity and Assembly Reliability", The 1997 International Flip Chip, Ball Grid Array, TAB and Advanced Packaging Swnposium Proceedings, Feb. 17-19, 1997.
4. R. Ghaffarian, N. Kim, "Ball Grid Reliability Assessment for Aerospace Applications," 30th International Symposium on Microelectronics, Philadelphia, Oct. 12-16, 1997
5. R. Ghaffarian, "A Review and Prediction of Chip State Package Assembly Reliability," 3oth International Symposium on Microelectronics, Oct 12-16, 1997

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